Risk Constrained Placement of Surge Arresters in Smart Power Systems

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Abstract— **The paper presents a novel algorithm to enhance the operational planning flexibility of protective measures of electromagnetic transients in smart power systems. The algorithm considers a risk constrained approach to place surge arresters and to enhance the power supply security. It facilitates a reduction in the number of surge arresters required for electromagnetic transient protection without taking a risk of damage to important equipment. For validation purposes, the algorithm has been implemented on a software environment with the IEEE 14 bus test system. Studies suggest that the algorithm reduces the hidden risks of electromagnetic transient events in smart power systems and enhance the equipment availability.**

***Index Terms*--Electromagnetic transient events, overvoltage protection, risk, surge arrester, security of power supply**

I. INTRODUCTION

Damage to equipment caused by lightning strikes and subsequent failure of power systems can be mitigated by installation of appropriate lightning protection schemes: most commonly lightning mast protection and overhead ground wire protection [1]. However, since lightning is unpredictable and has complex origins of behavior, current prevention schemes are susceptible to failure. The resultant electromagnetic transient overvoltage events occurring in a power system can have disastrous consequences, such as generation asynchronism, line overload and system collapse [2]. For this reason it is imperative that power systems are protected from physical lightning strikes and impacts during an event. Protective devices that are commonly utilized in modern power systems to mitigate electromagnetic transient effects are surge arresters [3]-[6].

Traditionally, surge arrester selection criteria have dictated that placement should be as close as is practical to the critical and important equipment, with their size adapted to energy absorption and overvoltage withstand requirements [6]-[7]. The theoretical framework supporting this design argues that an appropriately sized arrester can provide protection of electrical equipment by means of the creation of a low impedance path to ground during a severe overvoltage event [3]-[6]. Although traditional practice is rational, it is not always economically viable or robust in maintaining security of supply [7]. For example, in power systems where specific components (such as large generators) are critical to the supply capabilities of a network, these selection criteria may not provide optimal protection of the system to ensure the quality of supply. There are limited research publications on alternative surge arrester selection methods, with the exception of those proposed in [8]. Reference [8] evaluates the risk of failure of a surge arrester on the basis of physical transmission line tower configuration and the arrester itself.

This paper explores an alternative method to traditional surge arrester selection criteria for the purposes of protecting critical equipment in the context of operational planning in smart power systems. Electromagnetic transient analyses on power systems is needed assess potential 'at risk' components that are more susceptible to failure under transient conditions. These risk factors can be used to create guidelines to recommend best-practice of placement of surge arrester uncompromising the quality of supply. Current guidelines do not necessarily account for these 'at risk' locations, highlighting a limitation in knowledge on alternatives to current practice. The analysis of current practices in conjunction with electromagnetic transient studies make it possible to reinforce smart power systems so as to allow for more economical and robust surge arrester sizing and placement while constraining the risk and high economic costs. As the power systems are modernizing towards smart operation, such guidelines are needed in order to observe the full strength of smart grids.

The proposed approach addresses the risk categorization of a smart power system and how risk-constrained network planning can allow for a placement of surge arresters to mitigate electromagnetic transient impacts and to improve availability of important and critical equipment by taking into account the merits of smart operation of a power system.

II. THE APPROACH

A. *Lightning Modelling*

Results published by [9] determine that an average lightning stroke current is generally 31kA in magnitude with the last percentile values falling in the 100kA range. This distribution can be approximated by (1). [6]

$$P(I_S) = \frac{100}{1 + [\frac{I_S}{31}]^{2.6}} \tag{1}$$

where I_S is the stroke current amplitude in kA.

Using (1), it can be demonstrated that there is a 22.4% probability of any lightning strike exceeding a 50kA magnitude event. For this reason a 50kA magnitude strike is used in electromagnetic transient simulations, as it falls in the upper region of the distribution curve given in (1). The selected lightning stroke magnitude can vary, however saturation effects would need to be considered for each surge arrester. Reference [2] demonstrates that a lightning strike can be simulated by use of a bi-exponential function:

$$i(t) = I_0.(\exp(-\alpha t) - \exp(-\beta t)) \tag{2}$$

where I_0 is the lightning stroke current amplitude; α, β are constants determined by the wave front and half-amplitude time. Using a standard waveform of a wave-front time of 1.2µs and a half wave time of 50µs the constants α and β are set to 1.3×10^4 and 4.4×10^6 respectively. The implementation of the lightning current waveform generator can be realized as per Fig. 1:

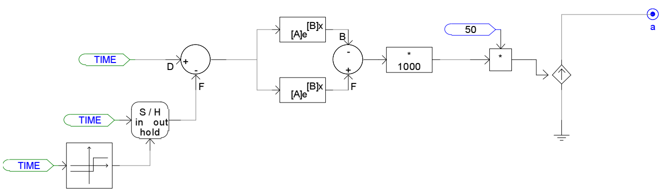

Fig.1. A simulated lightning waveform model

The utilization of the summation block in conjunction with the exponential blocks allows for the construction of the characteristic double exponential waveform of a lightning impulse. The multiplication block is used to convert the waveform from kilo Amps to Amps for accurate impulse simulation. The time related control logic involving the step function, the sample and hold block, and the summation block are used to designate at what time the lightning strike is to be applied to a power system. This is set to 2 seconds to allow for system disturbance to occur only during steady state operation as opposed to start-up conditions. The multiplication block is used to scale the exponential waveform to the desired lightning strike magnitude of 50kA. The dependent current source is used to propagate the lightning impulse waveform to the output for simulation.

B. System Reinforcement

The proposed approach considers the risks associated with smart power systems based on behaviours following electromagnetic transient events. These risks can be categorized based on

- Probability of a lightning strike occurring on an overhead transmission conductor
- Effect of removal of equipment or conductors on a system's load supplying ability
- Likelihood of failure of critical equipment (equipment that will cause system collapse following disconnection) after an electromagnetic transient event with no protective measures in place

Reference [10] highlights that an overhead conductor has a higher probability of being struck by lightning than that of a ground-lying component such as a network transformer or machine. Considering that preventative measures in the proposed approach are assumed to fail and geographical location is unknown, any branch in a power system in an overhead location is categorized as at high risk of strike, and any ground lying components are classed as at a low risk of strike. This 'high' and 'low' classification simplifies risk classification to a manageable level.

The effect of removal of equipment or conductors on the ability of the system to supply the required load can be determined by the application of load flow algorithms [10]. Disconnection of equipment demonstrates the susceptibility of a system to collapse during severe component- failing fault conditions. In some cases, removal of specific equipment such as large generators can cause other generators to exceed generation capacity, ultimately causing detriment to the security of supply. Equation (3) can be used to estimate the level of load increase or reduction that is required before system machines can operate within capability:

$$\Delta S_{Load}^{New} = \frac{\sum_{i=1}^{N} S_{i,Limit} - \alpha(S_{Gen}^{old} - S_{Load}^{old})}{S_{Load}^{old}} \times 100 \tag{3}$$

where ΔS_{Load}^{New} is the percentage load increase/reduction required, $S_{i,Limit}$ is the maximum generation possible for each machine in MW, S_{Gen}^{old} is the generation of all system machines under regular load conditions in MVA, S_{Load}^{old} is the regular load of the system in MVA, $S_{Gen}^{old} - S_{Load}^{old}$ is the MVA line losses of the system under regular load conditions, α is a constant that scales the line losses according to the load change, N is the number of machines in the system capable of generation. Load increase or reduction can also be affected through reactive power demands however reactive power demand can be supplied locally. Therefore, it is assumed that reactive power fluctuations are negligible. For networks where reactive power is significant, unable to be supplied locally or machines responsible for reactive power generation are already near steady state operating limits, reactive power variations should be accounted for.

The construction of a risk classification system highlighting events that are detrimental to security of supply is valuable in determining the electromagnetic transient effects on a system without surge protection. The proposed approach uses three classifications: low, high and extreme risk. Low risk classification is attributed to an electromagnetic transient event unlikely to cause a system failure. High risk refers to electromagnetic transient effects causing non-critical machines (machines that do not cause system collapse following disconnection) to become unstable. Extreme risk refers to electromagnetic transient effects causing damages to critical machines which can also lead to a system collapse.

The determination of these behaviours allows for the possibility of a risk assessment to be performed prior to proposals for system reinforcement. Fig. 2 outlines the steps of the proposed approach. Initially each branch in the transmission network is defined as overhead or ground-lying. This determines the high or low probability of lightning strike susceptibility. Following classification, each branch and bus location is categorized as an overhead conductor, network transformer or machine. It should be noted that a network transformer in this paper is identified as a transformer that is not directly connected to a generator in the network. Note that the loadability limits and surge effects on these transformers are excluded from the research due to their extra ability of thermal absorption compared to other equipment in a system. (Should the need arise, they could be incorporated in a particular system.) Next, the effect of bus removal is incorporated to categorize the supply capability of the system should component disconnection occur. For example, if the component disconnection causes system collapse then the corresponding bus is classed as having an extreme effect on security of power supply. In contrast if the component disconnection does not cause system collapse then the corresponding bus is classed as having a low effect on security of power supply. Critical machines are identified as equipment that are responsible for security of power supply and cause system collapse following disconnection. In contrast non-critical machines are those that supply the energy demand but do not compromise power supply security as a result of their unavailability.

The lightning strike depicted in Fig. 1 is applied to a single phase line that connects a bus. Following the application of strikes, the behavior of the system is investigated. A strike at a line location that does not cause system equipment damage does not require a surge arrester. In contrast, if a strike does cause equipment damage then they are to be identified. Following from this, if a critical machine is destabilized and the line location where the lightning strike occurs is near the terminal bus of a critical machine then a surge arrester is required to be connected at this location. This bus is then added to the 'critical zone'. Alternatively, if a critical machine is destabilized and the line where the lightning strike occurs is not connected to a terminal bus of a critical machine then this bus is added to the 'critical zone'. In contrast, if a critical machine is not destabilized and the line where the lightning strike occurs is not the terminal line of a non-critical machine then a surge arrester is not required at the line connected bus. Alternatively, if a critical machine is not destabilized and the line location where the lightning strike occurs is near the terminal bus of a non-critical machine then the bus is added to the 'non-critical machine zone'.

Following the classification of each bus and the construction of the critical and non-critical machine zones the network reinforcement solution is identified. New buses are constructed centrally to the 'critical zone' buses and 'non-critical zone' buses respectively. Each zone bus is connected to the corresponding central bus via new transmission lines. The algorithm terminates after each system bus is accounted for with surge arresters located at each of the newly constructed buses in the reinforced transmission network.

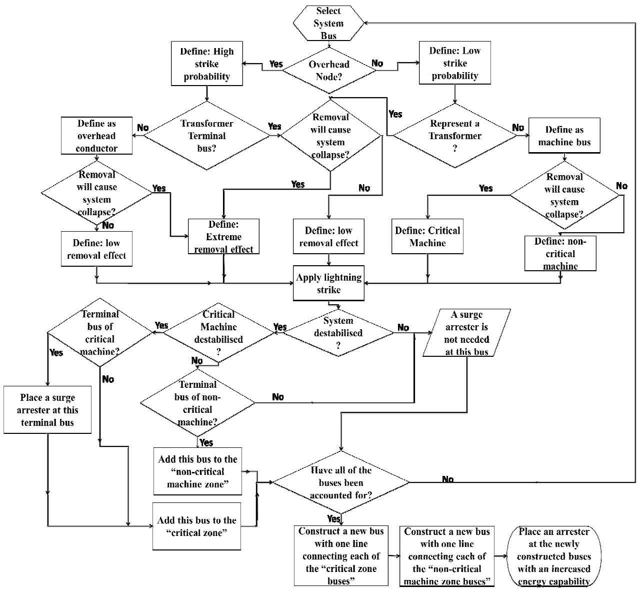

Fig. 2. Proposed risk-based surge arrester placement algorithm.

III. CASE STUDY

1) Network

The case study is aimed at determining a risk constrained network reinforcement solution to allow for effective surge arrester placement. IEEE 14 bus test system was used for the case study. The system consists of 5 synchronous machines, 3 of which are synchronous compensators with each equipped with IEEE type 1 excitation systems. There are a total of 11 loads in the sum of 259MW and 73.5MVAr. [11]

The RMS voltage chosen for buses 1-5 and 6-14 are 66kV and 11kV respectively with a 100MVA base. [12]

In electromagnetic transient studies it is required that synchronous machines are modeled with exciters and governors [13]. Machine data is shown in the Appendix with synchronous machine parameters and exciter data taken from [14] and [15] respectively. Governor data is from the hydro governor turbine model given in PSCAD/EMTDC [16].

The approach proposed in Section II is applied by integrating one bus site at a time. For example bus 3 is selected and put through the algorithm until its classification is completed. Then bus 4 is selected and put through the same procedure until all buses have been accounted for.

2) Electromagnetic Transient Response of the IEEE 14 Bus System

In order to determine areas of concern following an electromagnetic transient event that may cause system collapse, the following steps are required:

- Apply the lightning impulse model shown in Fig.1 on a single phase line connects at each bus
- Observe synchronous machine rotor angle results to determine if the equipment damage may occur.

A sample result for a lightning strike occurring at a line location near bus 3 is given in Fig. 3. Delta G1 to Delta G5 represents the rotor angles of machines 1 to 5 with the colours blue, purple, cyan, red and green representing machines 1 to 5 respectively.

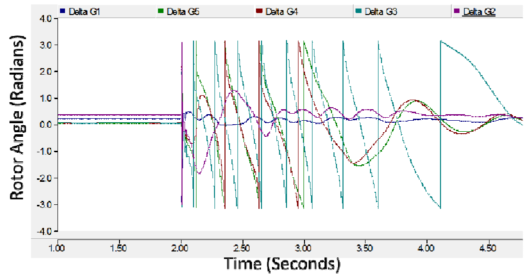

Fig. 3. Rotor angle response for a lightning strike occurring at a line connected at bus 3

A summary of the results following a strike on a line connected to each bus is given in Table I.

TABLE I
MACHINES IN THE IEEE 14 BUS SYSTEM THAT BECOME UNSTABLE FOLLOWING AN ELECTROMAGNETIC TRANSIENT EVENT

The line location, with respect to the bus, that experiences a lightning strike	Machines that become Unstable
1	1, 2, 3, 4, 5
2	1, 2, 3, 4, 5
3	1, 2, 3, 4, 5
4	3, 4, 5
5	1, 2, 3, 4, 5
6	5
7	None
8	4
9	None
10	None
11	None
12	None
13	None
14	None

3) Electromagnetic Transient Response of the IEEE 14 Bus System with Surge Arrester Reinforcement scheme

According to [6], the most ideal placement of an arrester is directly at the terminals of the equipment to be protected. It is assumed in this case that it is possible to place the arresters at the terminal bus of each synchronous machine in the test system. This results in 5 arresters being required according to modern practices. Arrester maximum continuous operating voltage is taken as 1.08pu with temporary overvoltage ratings as 1.25pu [17]. Application of the methodology proposed in Section II.B advanced the results shown in Table II.

TABLE II
MACHINES IN THE IEEE 14 BUS SYSTEM THAT BECOME UNSTABLE FOLLOWING AN ELECTROMAGNETIC TRANSIENT EVENT WITH THE PROPOSED METHODOLOGY

The line location, with respect to the bus, that experiences a lightning strike	Machines that become Unstable
1	None
2	None
3	3
4	3
5	None
6	5
7	4
8	4, 5
9	None
10	None
11	None
12	None
13	None
14	None

An extract of a result for a strike on a single phase line at bus 3 is given in Fig. 4.

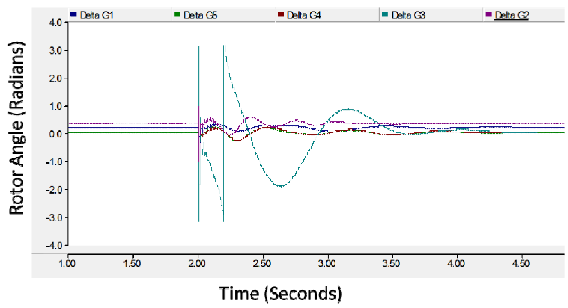

Fig. 4. Arrester reinforced rotor angle response for a lightning strike at a line connected at bus 3

4) Effect of Synchronous Machine Disconnection

Having determined the electromagnetic transient response of the IEEE 14 bus system with and without surge arrester reinforcement, it is imperative to determine the capabilities of the system following the disconnection of a load bearing machine. This is done through the steps:

1. Remove a machine from the system
2. Run a Newton-Raphson load flow to determine if the system is capable of compensation to supply the load

Using the above steps in conjunction with (3) the effect of machine disconnection can be determined. Given that Machine 1 and Machine 2 in the IEEE 14 bus system are the only sources of real power generation, only these machines are investigated for the effects of machine disconnection. Results are shown in Table III.

TABLE III
EFFECT OF SYNCHRONOUS MACHINE REMOVAL ON THE IEEE 14 BUS SYSTEM

Machine Removed	Variation level of loads (ΔS_{Load}^{New})
1	81% load decrease
2	131% load increase

From the observation of Table III it is apparent that

Machine 1 (the largest machine responsible for real power generation) is critical to maintain the security of power supply, since the system load needs to be decreased by 81% for Machine 2 to be able to sustain supply.

5) Risk Classification of the IEEE 14 Bus System

Observation of Fig. 3 shows that buses 1, 2, 3 and 8 are the terminal buses of each synchronous machine. This implies that these buses are in close to ground locations hence are classed as at low risk of strike. Bus locations 4, 5, 7 and 9 are shown as terminal buses to network transformers. These network transformers are assumed to be close to ground [11] and are therefore classed as at low risk of strike. All remaining buses connecting branches are overhead lines hence are classed as at high risk of strike.

Since observation of results from Section III.D indicates that Machine 1 is the only critical machine in the IEEE 14 bus system, the terminal bus of Machine 1 (bus 1) is classed as an extreme risk component as its disconnection results in system collapse. All remaining bus and corresponding branch locations are shown not to cause system collapse hence are classed as low risk components.

Observation of results in Table I demonstrate that strike on lines connected at bus locations 1, 2, 3 and 5 form the 'critical zone' of the system causes a damage to Machine 1. This follows that bus locations 1, 2, 3 and 5 are classed as extreme risk components. A lightning strike near the lines connected at buses 4, 6 and 8 would cause one or more 'non-critical' machines to be damaged. This results in the classification of these components as high risk. All remaining bus and branch locations caused negligible disturbance to system operation following an electromagnetic transient event hence are classed as low risk components. This is reflected in the risk diagram shown in Fig. 5.

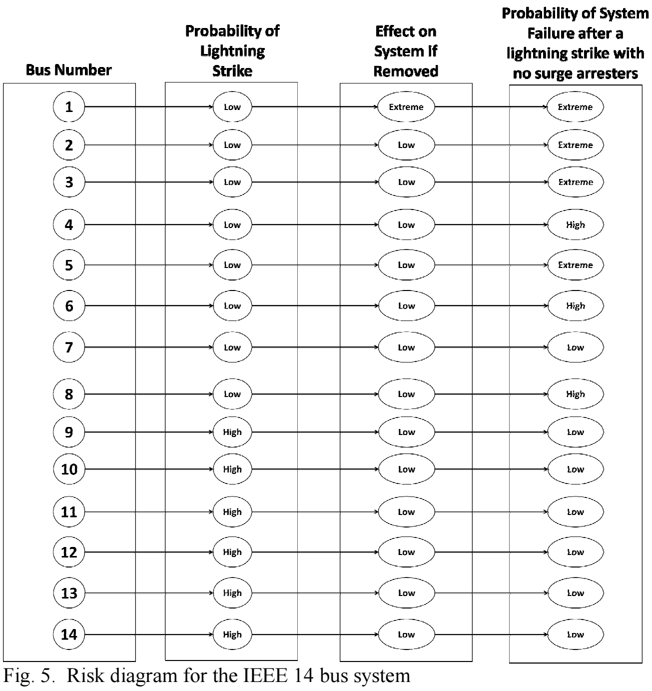

Fig. 5. Risk diagram for the IEEE 14 bus system

IV. CONCLUSION

The paper proposes a surge arrester placement algorithm based on risks associated with protecting critical and other equipment. The algorithm categorizes system components based on event probabilities and the effects on system integrity, offering reinforcement solutions that can potentially mitigate the risk of system failure.

Results of the study argue that risk categorization is plausible for power systems based on probabilistic events. Risk-based placement of surge arresters is more efficient at maintaining system integrity without detriment to the security of energy supply, while protecting critical and other equipment. The approach enables a reduction in surge arresters, uncompromising the risk of equipment damage.

The classification of equipment based on probability of events as well as the electromagnetic transient impacts can guide risk-based protocols for the placement of surge arresters and to avoid equipment damage. In that context, the proposed algorithm offers a considerable value for expansion planning and to enhance the security of energy supply in a smart power system.

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